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Exposure Reduction to Human Bio-effluents Using Seat-integrated Localized Ventilation in Quiescent Indoor Environment

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Abstract

Local airflows generated from people such as the natural convection flow may determine the distribution of pollutants indoors. New seat-integrated ventilated method was developed to improve the inhaled air quality of occupants while sitting. The method named “Ventilated Cushion” was designed to suck gaseous pollutants (i.e. bio-effluents) emitted from the body of a sedentary person and exhaust them before they entrained in the person’s breathing zone or mix with the surrounding air. Full-scale experiments were performed in a climate chamber. The chamber was ventilated by an upward piston flow through the floor. A sitting person was simulated using a dressed thermal manikin which had a body shape and surface temperature distribution of a real average person under state of thermal comfort. The chair on which the thermal manikin was sitting was equipped with the ventilated cushion (VC). The interaction between the natural convection flow around the human body and the suction from the VC was studied in terms of transport of gaseous pollutants. The experiments were conducted at two room air temperatures. The performance of the VC was assessed by measuring the pollution concentration in the breathing zone of the manikin and at 0.5 m above the head of the manikin. The results showed that the concentration of the pollutants decreased when the VC was in operation. The results from this study showed that the use of the VC provides an efficient method for control of body-emitted gaseous pollutants in order to improve the inhaled air and indoor air quality.

Keywords - personal exposure; localized ventilation; airflow interaction; airborne pollutants; indoor air quality

1. Introduction

In densely populated indoor environments (e.g. theatres, cinemas, public transport, etc.), contaminants generated by occupants can significantly reduce the quality of inhaled air. People release not only CO₂ and other compounds while exhaling air, but

also they emit different gaseous compounds from their bodies normally called bio-effluents. Volatile organic compounds (VOCs) are one of the bio-effluent contaminants that are produced by the skin. Production of VOCs by the human skin is governed mainly by the secretion of apocrine and sebaceous glands [1]. Apocrine glands are located in the axillae, genital area and areolas, and their secretions are main source of odorants [2]. Sebaceous glands, which secrete sebum and lipids, are distributed all over the body. Secretions from these glands provide favorable environment for numerous populations of microorganisms which are considered key contributors to the formation of human body odor [3].

A building occupant can be exposed to his/her own contaminants as well as contaminants found in the background air. A recent study has reported that in a room with low air velocities the convective boundary layer (CBL) around a sitting person can entrain gaseous pollutants from the surrounding air and transport them to the breathing zone [4]. Licina et al. [4] also found that the concentration in the breathing zone was the highest when the gaseous contaminant was released from the person's body. The CBL is formed by the natural convection produced by the human body in a quiescent environment which transforms into a thermal plume that rises above the head [5]. There is a growing body of literature that recognizes the importance of the CBL for its ability to transport various pollutants to the inhalation zone of occupants [4-8]. A control strategy, therefore, is needed to protect the inhaled air of occupants not to be polluted.

The current total volume air distribution principles (i.e. mixing and displacement ventilation) usually supply large volume of air to the room in order to dilute the air pollution. However, supplying high amount of fresh air is not always effective to reduce occupants' exposure near the contaminant source where dilution has not yet occurred. Studies have reported an interesting phenomenon showing that increased ventilation rate from 6 to 12 ACH in rooms increases the occupants' exposure to cough-released air [9, 10]. A more efficient method for exposure reduction is to capture the pollutants at their source before they entrained in the person's breathing zone or mix with the surrounding environment.

A novel localized exhaust method recently has been developed and studied for its efficiency to remove human body-emitted bio-effluents while a person is in bed. A ventilated mattress (VM) with local exhaust openings was used to evacuate the simulated bio-effluents from armpits, groin region and feet before being spread in the room [11, 12]. It was reported that the VM (exhausting only 1.5 L/s of air) in conjunction with mixing ventilation at 1.5 air changes per hour (ACH) in the background can reduce the measured concentrations of bio-effluents at the breathing zone compared to the measured concentrations under mixing ventilation at 3 or 6 ACH and without using the VM [11].

The purpose of the present study was to implement local exhaust ventilation, such as the VM, into a cushion for a seat and identify its efficiency for capturing body-emitted gaseous pollutants in a quiescent indoor environment. The study focuses also on the interaction between the natural convective flow around a human body and the suction from the ventilated cushion.

1. Methods

Full-scale experiments with a sitting thermal manikin were performed in a climate chamber with controlled air temperature and room ventilation rate. The climate chamber had dimensions of 4.7 m x 5.8 m x 2.5 m (W x L x H). The chamber was ventilated by an upward piston flow supplied through the floor, which was built of a porous sheet covered by a steel floor grating placed on the top. The air was exhausted through an opening (with free-flow area of $2.4 \times 2.4 \text{ m}^2$) in the ceiling above the manikin. The construction of the test room ensures a condition with uniform temperature field and air velocity lower than 0.05 m/s. From inside, the chamber had double walls which consisted of inner vinyl sheets forming a curtain distanced 1.6 cm from the solid mother wall. This kind of construction allowed part of the supplied room air to flow behind the curtain and to ensure a mean radiant temperature equal to the room air temperature and negligible radiant temperature asymmetry. The room air temperature could be changed rapidly and regulated within the range between 5 °C and 50 °C with an accuracy of $\pm 0.2 \text{ °C}$. The temperature in the room was regulated by changing the set point temperature in the software of the control PC of the system. The temperature sensor was kept in the room at 1.2 m height.

The supply air in the chamber was 100% outdoor air with no recirculation. The airflow was regulated manually by adjusting the variable speed drive frequency of the ventilation system's fan. The frequency of the fan was adjusted to be 40% resulting in air velocity in the chamber less than 0.05 m/s. The air velocity was measured using an omnidirectional draught probe SWA 03 connected to a measuring instrument Swema 3000 (accuracy of measurements is $\pm 0.03 \text{ m/s}$). Additionally, a wooden plate ($2 \times 1.54 \text{ m}^2$) was put under the manikin to prevent the supply airflow to disrupt the natural convection produced by the thermal manikin. In this way, the air motion in the vicinity of the manikin was generated only due to the manikin's body heat.

During the measurements, a calibrated non-breathing thermal manikin was used to realistically simulate a sitting person. The manikin resembled an average Scandinavian woman of height 1.7 m. The manikin height in the current study was 1.23 m in the sitting posture. In order to produce heat as a real person, the manikin was set to work in a "comfort mode" (light sedentary activity). For this regulation principle the surface of the manikin's body has a temperature distribution, similar to the skin temperature of an average human under thermal comfort. Measurements under winter and summer conditions were performed. During the wintertime experimental conditions the manikin was dressed in panties, singlet, light-weight long sleeve blouse, thick sweater, normal trousers, thick long socks and thin soled shoes. According to the European Standard [13] this clothing resulted in Clo value of 1. During the summertime conditions the manikin was dressed in panties, short sleeve shirt, normal trousers, normal socks and thin soled shoes with the overall Clo value of 0.47.

Two tracer gases, namely carbon dioxide (CO_2) and nitrous oxide (N_2O), were used to simulate bio-effluents generated by the manikin's armpits and groin region respectively. The tracer gases were dosed at constant emission rates directly from compressed gas cylinders. The gas was transported from the cylinders to the manikin

through separate pipes and released through porous sponges that were fixed to the end of the pipes and attached to the polluting body parts. The emission rate of CO₂ and N₂O were adjusted to be 1.2 L/min and 0.1 L/min respectively.

The manikin was located in the middle of the chamber and it was sitting on a computer chair (Fig. 1). On top of the chair the so-called “Ventilated cushion” (VC) was placed. The ventilated cushion was used in some of the experiments to exhaust locally the contaminants emitted from the manikin’s body. Along the surface of the VC there were eight rows of small openings each with diameter of 6 mm. There were two openings per row and the distance between them was 0.135 m. The VC was connected to a local exhaust system which was able to suck air through the openings and exhaust it out of the chamber. A plastic mesh inside the ventilated cushion was built-in which provided support and allowed the exhaust air to move inside the cushion. During the measurements, the exhaust airflow rate of the VC was provided by an axial fan (located outside the chamber) connected to the VC with flexible and straight ducts (Ø 0.08 m). The airflow rate through the VM was measured with the help of an air flow sensor (MFS-C-080) installed in the straight connection between the fan and the VC. The maximum error in the measurement with this sensor is ± 3 % of the actual flow. The pressure difference at the MFS sensor was measured with a differential pressure micro-manometer FCO510 (accuracy of 0.01 Pa [0.15×10^{-5} psi] $\pm 0.25\%$ of reading). Based on the pressure difference readings from the micro-manometer, the desired flow rate was adjusted by a manually operated damper. The performance of the VC was tested at two exhaust flow rates - 1.5 L/s and 5 L/s.

The interaction between the natural convective flow around the manikin’s body and the suction of the VC was investigated at room air temperature of 20 and 26 °C. Reference experiments were conducted at both temperature levels when the ventilated cushion was not working. The air mixed with the tracer gases was sampled and its gas concentration was analysed under steady-state conditions using an Innova 1303 multi-channel sampler and a photoacoustic multi-gas monitor Innova 1312. The instruments were placed outside the chamber. The gases were sampled through nylon tubes in diameter 4 mm. The tubes were placed at the mouth of the manikin, 0.5 m above the head, at the supply and total exhaust air. At each sampling point, 40 values of tracer gas concentration were collected after reaching steady state.

In order to quantify the efficiency of the VC, the obtained concentrations were normalized as follows:

$$\text{Normalized concentration} = C_{i,\text{avg}}/C_{i,\text{avg,Ref}} \quad (1)$$

where $C_{i,\text{avg}}$ is the concentration acquired at the sampling location, $C_{i,\text{avg,Ref}}$ is the concentration acquired at the same sampling location during the reference case when the VC was not operating. The value of the normalized concentration lower than “1” shows that the concentration of pollutants at the measuring point is lower compared to the reference case, i.e. the local exhaust work well, and vice versa when the value is higher than “1”.

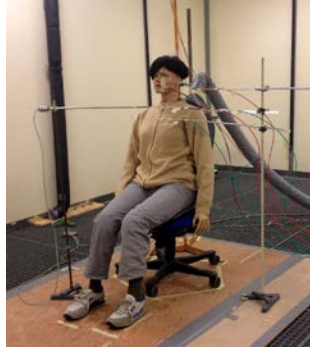
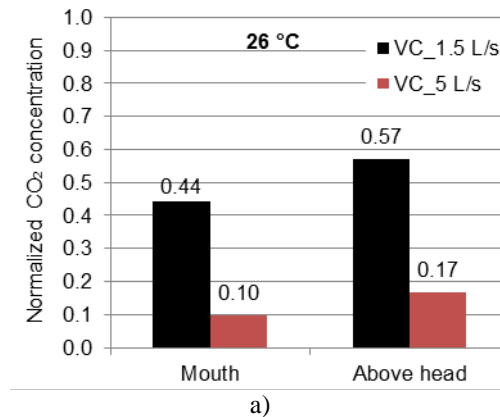


Fig. 1 Experimental set-up showing the manikin's outfit during wintertime conditions

2. Results and Discussions

The results of the normalized concentration at the mouth and above the head for both temperature levels and pollution source being the armpits are shown in Fig. 3a and 3b. It can be seen in both figures that the normalized values are all below 1. This means that the ventilated cushion was able to capture the emitted pollutants from the armpits and discharged them out of the chamber. As expected, the performance of the VC was better at airflow rate of 5 L/s compared to the results with 1.5 L/s exhaust flow rate. In fact, the pollutants were almost entirely exhausted by the VC when operating at 5 L/s. It is interesting that the measured concentrations at both mouth and above head at 26 °C are lower than the concentrations at 20°C. This trend is apparent during the case when the VC was operating at 1.5 L/s.



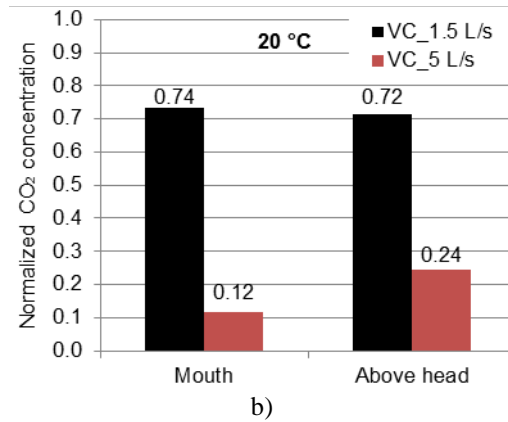
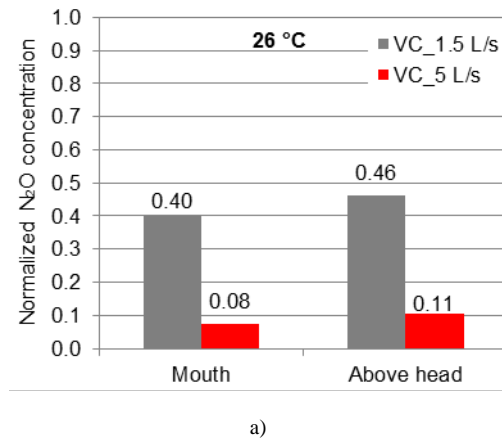
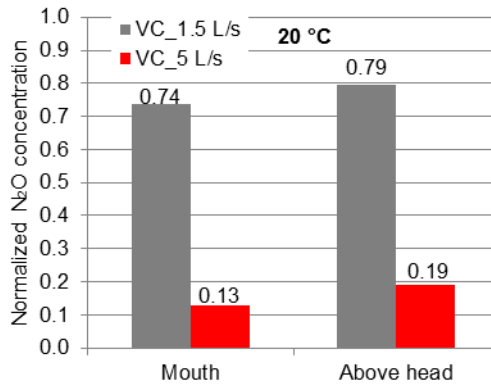


Fig. 2 Normalized concentration of the pollutants emitted from the armpits (CO₂ tracer gas) at a) 26 °C and b) 20 °C

The results in Fig. 3a and Fig. 3b show the normalized concentration obtained for the pollutants released from the groin region of the thermal manikin. It can be seen that the normalized values do not differ from the results obtained for the armpit-emitted pollutants (Fig. 2). In Fig 3 the concentration at the mouth and above the head decreased with the increase of the exhaust flowrate through the VC. The tendency was observed during both conditions – 26 °C and 20 °C (Fig. 3).





b)

Fig. 3 Normalized concentration of the pollutants emitted from the groin area (N₂O tracer gas) at a) 26 °C and b) 20 °C

Overall, the results from this study show that the cushion-integrated localized exhaust, namely the VC, is capable of capturing gaseous pollutants released from the groins and armpits when a person is sitting on the VC. These results are promising considering potential applications of the ventilated cushion for personal exposure reduction in indoor settings.

When the VC flow rate was 1.5 L/s, there is a tendency that the measured concentrations at 26 °C are lower than the ones at 20 °C. The reason could be that at high room temperature the free convection flow is weaker (i.e. the velocities are lower), thus the upward transportation of the pollutants is also weaker. This effect has been reported by Licina et al. [14]. The study show that an increase of the ambient temperature from 20 to 26 °C widens the CBL flow in front of a sitting person and causes a reduction of the peak velocity from 0.24 to 0.16 m/s Therefore, the interaction between the free convective flow and the exhaust flow through the VC resulted in more pollutants evacuated by the VC at 26 °C compared to at 20 °C when the CBL of the manikin was stronger and more pollutants managed to escape. It should be noted that when the room air temperature changed from 20 to 26 °C, the clothing insulation also changed from 1 Clo to 0.47 Clo (as this is what would happen realistically – lighter clothes at summer conditions and thicker clothes at winter conditions). It has been documented that high clothing insulation decreases the velocity of the CBL in the facial region. The strength of the CBL depends also on the clothing surface temperature. The higher the temperature difference between the clothing surface temperature and the ambient temperature, the stronger the CBL becomes [14]. In cooler environment it is expected that an increase of the clothing insulation will decrease the clothing surface temperature because less heat will be exchanged with the warm body. This will weaken

the boundary layer. However, at the same time the strength of the boundary layer will increase because ambient temperature will be lower. This is an important issue for future research. Parameters such as thermal insulation, type of clothing (e.g. loose or tight clothes), and even hair style will influence the development of the CBL. This, in turn, can affect the performance of the VC as it was observed from the current results.

As the results obtained for the two pollutants show, the efficiency of the VC was not affected by the position of the source (groins and armpits). This is an important finding, since it has been reported that in a quiescent indoor environment different source locations (near the body) create large discrepancies in personal exposure and distribution of the pollution in the breathing zone [4]. Moreover, the CBL has the ability to transport gaseous pollutants, which are close to the human body, to the upper room level through the thermal plume formed above the head. This was observed also in the present study when the VC's flow rate was 1.5 L/s. The results show that the measured pollutants at the mouth spread above the head. In this way, the pollutants can be exhausted or mixed with the room air [4]. Therefore, it is expected that the VC, operating at 5 L/s, will improve the quality of inhaled air in terms of body-emitted gaseous pollutants since it will prevent their spread.

It should be noted that the practical application of the VC may be changed under different room conditions and occupant behavior. The current study does not take into account different body postures, human breathing, different outfits and physical movements when a person is sitting. The thermal comfort of the person sitting on the VC also might be an issue. In fact, this has been investigated and the results are going to be published in a separate study.

3. Conclusions

The present study was set out to examine the interaction between the free convection flow around manikin's body and the exhaust airflow of the VC at two room air temperatures. The results performed in a quiescent uniform environment showed that the concentration of the pollutants at the breathing zone decreased when the VC was in operation. This study has identified that the VC has an impact on the formation of the CBL around the body of an occupant. The exhaust flow of the VC can become governing out of other factors such as room air temperature and clothing in terms of bio-effluent transportation to the breathing zone by the CBL. The inhaled air quality is influenced by the interaction between the CBL and the exhaust airflow of the VC. The control of the interaction between the CBL and the VC's exhaust flow needs to be further studied. The application of VC in highly occupied spaces, e.g. cinemas, theaters, and public transport, has to be considered. Energy can be saved by using such localized exhaust nears the pollution source to minimize the spread of pollutants indoors instead of ventilating the entire space.

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